A SENSOR WEB SIMULATOR FOR DESIGN OF NEW EARTH SCIENCE OBSERVING SYSTEMS

Michael S. Seablom and Stephen J. Talabac
NASA Goddard Space Flight Center, Greenbelt, MD

Joseph Ardizzone and Joseph Terry
Science Applications International Corporation, McLean, VA

ABSTRACT

A strategic goal of NASA's Science Mission Directorate is the development of highly advanced global Earth observing systems to help monitor and predict key elements of the Earth's ocean-atmosphere system. A new concept now being considered is the "sensor web", which would allow collaborative measurements to be made by linking together various spaced-based and in situ observations along with output from numerical models. A underlying sophisticated communications fabric would enable rapid, seamless interaction across observing platforms and between observations and Earth system models. For weather forecasting applications, we envision a future architecture in which Earth observing systems are coupled with many different atmospheric, chemical, and oceanographic models and data assimilation systems such that our ability to monitor, understand, and predict the evolution of rapidly evolving, transient, or variable features in the atmosphere are better understood. In theory, tasking the observing system to collect data at specific locations in space and time could produce notable gains in predictive skill. In 2006 our team was awarded funding from NASA's Earth Science Technology Office (ESTO) to design and build an end-to-end sensor web simulator (SWS) based upon the proposed architecture that would objectively assess the scientific value of a fully functional model-driven meteorological sensor web. The effort is based upon two ESTO-funded studies [1], [2] that have yielded a next-generation weather observing system architecture and a preliminary SWS software architecture developed in 2003. Simulation is essential: investing in the design and implementation of such a complex observing system could be potentially costly and almost certainly involve significant risk. The SWS will help provide information systems engineers and Earth scientists with the ability to define and model candidate designs, and to quantitatively measure predictive forecast skill improvements. We will report on our efforts to develop a prototype simulator for a weather forecasting application, and present preliminary results in which the steps of the simulator were manually executed.

1. APPROACH

We have selected a future operational wind lidar mission, the Global Wind Observing Sounder (GWOS) [3], as a use case for demonstration. Using sensor web concepts we will show preliminary results from the simulation of spacecraft operations that would enable targeted lidar data collection, through the use of off-nadir slewing, for specific regions of the atmosphere that would most likely have the greatest impact on weather forecast skill. For this experiment we have made use of estimates of the model's forecast error to direct the lidar to collect data in those regions of the atmosphere that are estimated to be in a state of low predictability. Through the use of synthetic lidar data we have completed a set of experiments to examine the impact of adaptive targeting on multiple data assimilation cycles. Preliminary results indicate that invoking spacecraft slewing increases the number of atmospheric targets that fall within the lidar telescopes' fields of view by up to 33%, and based upon anomaly correlation scores there is "significant" improvement in predictive skill.

The development of atmospheric numerical models over the past four decades has helped to improve weather prediction by linking together the many atmospheric and oceanic observations through data assimilation and by applying appropriate constraints based upon the governing equations. Predictive skill of the state-of-the-art atmospheric models have slowly improved over this time: presently it is approaching 9 days. There have been a number of evolutionary developments that have contributed to the improvement in skill: (i) more numerous and better quality satellites observations; (ii) improvements in numerical techniques employed by the numerical models and the data analysis schemes; and (iii) computational and networking infrastructure improvements.

Operational use of "targeted observations" could facilitate the evolution of predictive skill. NASA and NOAA studies have investigated techniques to identify critical regions of the atmosphere that are highly sensitive to analysis errors. Increased data sampling in these regions has, in some instances, resulted in better predictive skill [5]. The ability to extrapolate this capability to a global scale and

interact with the full suite of observational assets will ultimately determine the full potential of the technique.

Implementation of an operational national forecasting system that includes autonomous targeted observations would be costly and would involve risk. New technologies would need to be developed for integrating disparate hardware and software components that would collect observations, perform quality control, analyze data, perform numerical forecasts, identify where new observations are required, initiate planning and scheduling, and perform command and control for the end-to-end observing system. Aside from the engineering challenges, the mathematical complexities of data assimilation and the chaotic nature of the atmosphere ensure there are no guarantees that the suggested sensor web would be a panacea for improving predictive skill. The SWS is a critical first step in the development path of using intelligent targeting for operational data assimilation and forecasting. Many parameters control the behavior of the simulated observing system (e.g., varying instrument operating modes; communications architecture). The SWS will permit the user to modify the values of these parameters thus enabling trades analyses to be performed. By exploring "What-if?" operations concepts and scenarios, the SWS will become a valuable decision support tool to quantitatively assess the value of alternative intelligent targeting schemes toward predictive skill improvement, and permit the user to weigh science benefits versus the observing system's complexity and cost. Our approach to an operational model-driven sensor web is described in [2]. Six components comprise the major SWS functions [4].

(1) Observing System: provides data to the simulation environment, either through the use of historical case studies or, in the case of a simulation of a future instrument, Observing System Simulation Experiments (OSSEs) are performed by this component to generate realistic, synthetic measurement data.
(2) Data Processing: performs data selection and quality control.
(3) Prediction System: performs the major roles of data assimilation and numerical prediction.
(4) Targeted Observing: provides requests for observations over a specific location and time.
(6) External Control System: matches asset capabilities with targeting requests and produces an optimized targeting request for the Command and Control component.
(6) Command and Control: performs the scheduling and issues the necessary commands to modify the normal behavior of an asset (e.g., switch to high data-rate collection).

2. GWOS MISSION OVERVIEW

Two laser subsystems comprise the GWOS lidar instrument: a direct detection 100 Hz pulse repetition frequency (PRF) subsystem and a coherent 5 Hz PRF subsystem. The two subsystems operate through four telescopes: two forward-pointing and two aft-pointing with each oriented nominally ±45° in both azimuth and elevation relative to the spacecraft's velocity vector. Each telescope dwells for 12 seconds taking measurements (~86 km along the ground track) before transitioning to the next telescope in sequence. A 1.3 second latency is incurred between successive telescope dwell periods. Consecutive measurements by the same telescope repeat every 53.2 seconds (during which time the spacecraft has traveled 384 km along its ground track). For each of the four telescope azimuths, the direct detection laser integrates 1,200 shots (15 atmospheric layers) and the coherent laser subsystem integrates 60 shots (30 atmospheric layers) yielding LOS measurements at 45 atmospheric layers. To obtain horizontal u,v wind vector components at multiple atmosperic layers, the lidars sample an air parcel by taking LOS measurements from two viewing perspectives. Approximately 81 seconds after the fore-shot telescope measurements are made, the spacecraft's position along its orbital path permits the aft-viewing telescopes to direct the laser beams to make LOS measurements of approximately the same air parcel. By combining the fore and aft LOS shots, u,v wind vector components at 45 atmospheric layers are derived. During its 2 year mission lifetime, the coherent detection subsystem will take approximately 300 million shots, whereas the direct detection laser subsystem will take approximately 6 billion shots. We investigated a modification to the GWOS operations concept that would: (i) minimize the required number of shots without compromising information of the atmospheric state, and (ii) target data collection for specific regions of the atmosphere that would potentially have the greatest impact on forecast skill. In the first case GWOS would be provided the first guess wind field from a global forecast model. Observed LOS winds from the fore shot would be compared with the predicted winds from the model and valid at the time of the observation. If the observed and predicted values were in adequate agreement the aft shot would not be performed. If such agreement were ubiquitous there could be a substantial reduction in the lidar's duty cycle potentially extending the life of the instrument. In the second case we would use estimates of the model's forecast error to slew the spacecraft to target regions of the atmosphere estimated to be in a state of low predictability, and/or target sensible weather features of interest.

3. DATA VOLUME ESTIMATES

The 400km circular GWOS orbit (92.56 minutes orbital period) yields 18,790 LOS values per orbit. In one day (15.5 orbits) 291,251 LOS values are generated. In one estimate we assume 7 bytes are used to represent the LOS data and associated meta data yielding 131.5 KB/orbit (2.04MB/day). For the first use case where no slewing occurs, this volume of predicted LOS values could be uplinked using today's

forward link communications infrastructure. However, this operational concept requires continuous, accurate, and precise *a priori* knowledge of both the time and location of each laser measurement. Another method, potentially requiring orders of magnitude larger volumes of predicted LOS values to be uplinked to the spacecraft, is also being examined.

The Goddard Earth Observing System Model, Version 5 (GEOS-5) Data Analysis System integrates the GEOS-5 Advanced Global Circulation Model with the Gridpoint Statistical Interpolation atmospheric analysis package. We use the GEOS-5 model to generate predicted LOS wind vectors for each cell of a global, uniformly spaced gridded field. The current version of the model uses a 0.25 degree x 0.33 degree grid spacing (777,600 grid cells). At 45 atmospheric layers per cell, approximately 35 million LOS wind values are represented by the global gridded field. In one estimate we assume 7 bytes represent each predicted LOS value and related metadata potentially requiring 245 MB to be uploaded to the spacecraft. This estimated data volume can be greatly reduced. Since the model is presently updated every 6 hours, the GWOS spacecraft will have completed only ~4 orbits. There is no need to uplink predicted LOS wind data for regions that will not be within view of GWOS during a given 6 hour interval. Instead, only LOS values that are within the telescopes' field of view must be uplinked where they can be interpolated in space and time and compared with the actual measured LOS values. In the case where the spacecraft is slewed to target a particular region, an aft shot would always be made: thus predicted LOS values would not be required to be computed and uplinked. It is important to recognize however that future implementations of the GEOS-5 model are expected to utilize much finer grid scales (e.g., 0.1 x 0.1 degree grid) and a concomitant order of magnitude increase in predicted LOS data volumes will result. In addition, the frequency of model runs will almost certainly increase as computing capacity increases over time. The SWS design cannot assume present day capabilities: it must permit the user to adjust the values of these parameters and facilitate a wide range of "What-if?" analyses.

4. COMMUNICATIONS ARCHITECTURE

The underlying communications architecture must provide services to periodically uplink potentially tens and perhaps hundreds of megabytes of predicted wind field data to the spacecraft. This is a new mission operations concept: a seamless, integrated space-ground communications infrastructure to provide these services is not presently available. The ability to uplink large data volumes requires on-demand availability of wideband terrestrial networks and forward links, and frequent spacecraft contact opportunities to uplink targeting information on demand. We have identified three candidate forward link communications architectures and we are assessing their potential to provide

the required uplink data services.

1. **Non-TDRS "traditional" ground stations**: One to fifteen worldwide sites having 1 Mbps S-band or 25 Mbps Ka-band uplink capability.
2. **TDRS architecture with enhanced ground station capacity**: 1 Mbps S-band or 25 Mbps Ka-band single access (SA) forward links
3. **Future hybrid RF/optical space network**: RF up/down links and optical crosslinks >100 Mbps.

We identified available space- and ground-segment forward-link capabilities and capacities and potential modifications to: (i) augment existing and planned ground station capabilities, and (ii) implement hardware and software upgrades to Tracking and Data Relay Satellite (TDRS) forward link facilities as two approaches with which to provide the required services prior to the year 2030. Emerging hybrid RF/optical crosslink technologies that could become available after 2030 are also being evaluated. We are using Analytical Graphics Inc. Satellite Tool Kit to evaluate these communications alternatives for both the nominal and slewing measurement modes. For non-TDRS traditional ground station alternatives, we are also performing trades analyses that examine data uplink rates versus the quantity and distribution of worldwide ground stations. One candidate approach we are examining augments the 15 ground receiving stations proposed for the NPOESS SafetyNet ground system architecture with a forward link capability.

5. SIMULATION PRELIMINARY TEST RESULTS

We emphasize that at this stage of the project the purpose of our experiments is to help design the simulator, and is not meant to draw definitive conclusions regarding the two operations concept configurations: lidar duty cycle reduction and targeted observations. In the third year of the project we intend to conduct a more formal observing system simulation experiment (OSSE) under the direction of a senior scientist and under the review of the NASA Global Modeling and Assimilation Office.

To help guide the SWS design, a "zeroth-order" simulation was set up and executed that tested the use of model-directed observations. Synthetic observations based upon the proposed GWOS mission were used and major components of the simulator were run manually and sequentially. Through our partnership with Simpson Weather Associates, Inc., we acquired a sufficiently large sample of simulated conical-scanning lidar sub-sampled to simulate GWOS look angles. Data analysis was performed using NOAA's Gridpoint Statistical Interpolation (GSI). For the nominal non-slewing mode we set up three cases: a control which used no lidar data; another in which lidar data were used only where there was "significant" disagreement with the forecast winds; and third in which all lidar data

were used. Because the current version of the GSI does not support assimilation of line-of-sight winds our experiment made use of only the *u* vector wind components to serve as a proxy for the line-of-sight lidar measurements. The model's first guess *u* wind components were compared to the simulated lidar *u* wind components. Where the differences were within a pre-defined value (ε) data were withheld from the assimilation process, in essence "turning off" the aft shot. Changing the values of ε would allow mission designers to weigh the benefit of reducing the lidar's duty cycle against the overall impact to the science.

A 20-day period was selected for executing the three configurations. Five day forecasts were launched from each of the 00Z assimilation periods. In the targeting configuration we defined a range of values for ε from $\varepsilon=1.8\text{ms}^{-1}$ (lowest point in the atmosphere) to $\varepsilon=3.0\text{ms}^{-1}$ (uppermost point in the atmosphere). Lidar data in which the "observed" wind was within the corresponding value of ε of the model's first guess value were removed. For this sample period nearly 80% of the data met the criterion and were prevented from being included in the data assimilation cycle. In operations this would translate to a duty cycle reduction of about 30%. To test whether the duty cycle reduction had any negative impact on the forecast skill we employed the commonly-applied anomaly correlation. Not surprisingly, the full lidar set has the highest correlation while the control set (no lidar data) has the worst. When the targeted data were deleted from the assimilation the Northern Hemisphere results indicate little degradation; for the Southern Hemisphere the results are more ambiguous.

We also conducted experiments to examine the impact of slewing GWOS for adaptive targeting. This included identifying "sensitive regions" in the atmosphere (i.e., where the forecast is highly responsive to analysis errors) and autonomous detection of features of interest (e.g., tropical cyclones, jet streaks). Adjoint techniques have proven to be successful to calculate the sensitive regions of the atmosphere [6] and we plan to incorporate this technique now under development by GMAO scientists. Acknowledging the time constraints for the test case, we employed a less sophisticated method that calculated the difference between two 500hPa height forecast fields at 12-hour and a 36-hour verification times. If the atmosphere was in a perfectly predictable state the difference between the two forecasts should be zero. Large differences between the two forecasts would be used to make targeted lidar observations by slewing the spacecraft and targeting as many of the sensitive regions as possible. We also included a set of rule-based targets prioritized in the order of the following subcategories: the feature is (a) over land; (b) over the coastline; (c) over ocean but is approaching land; (d) over ocean moving away from land; (e) over ocean and is far from land (> 1000km). Features to be targeted and their ranking priorities (highest to lowest) were: tropical cyclones, extratropical cyclones, thermal advection centers, Jet centers, and deepening centers. To emulate the effects of

slewing we generated additional synthetic lidar data that were positioned ±150km off the viewing angle of the instrument. For this experiment preliminary results indicate that invoking spacecraft slewing increases the number of atmospheric targets that fall within the lidar telescopes' fields of view by up to 33%.

6. SUMMARY

The investigations described here are intended to provide examples of how the simulator would be used to explore mission formulation alternatives and, eventually, to support on-orbit mission operations. The lessons learned from the manual execution of the major elements will be used during the second year of the project to guide the final design and for constructing the final prototype. Although the results of these experiments have not been scientifically validated, they demonstrate that the types of "what if" scenarios likely to be performed by investigators making use of the simulator have a significant impact on predictive skill of the forecast model.

8. REFERENCES
[1] Steiner, M., Atlas, R., Clausen, M., Kalb, M., McConaughy, G., Muller, R., Neeck, S., Seablom, M., 2002: "Advanced Weather Prediction Technologies: NASA's Contribution to the Operational Agencies", Technical Report, NASA Earth Science Technology Office.

[2] Higgins, G., M. Kalb, R. Lutz, R. Mahoney, R. Mauk, M. Seablom, and S. Talabac, 2003: "Advanced Weather Prediction Technologies: Two-way Interactive Sensor Web and Modeling System, Phase II Vision Architecture Study", Technical Memo, NASA Earth Science Technology Office.

[3] Kakar, R., Neeck, S., Bajpayee, J., Shaw, H., Gentry, B., Kavaya, M., Sing, U., "Overview of An Advanced Earth Science Mission Concept Study for a Global Wind Observing Sounder"; Study slides, January 2007.

[4] Seablom, M., Talabac, S., Higgins, G., and Womack, B., 2007: The Applicability of a Sensor Web Simulator to Evaluate a Future Lidar Mission. Preprints for the 2007 NASA Science Technology Conference, June, 2007, NASA Earth Science Technology Office.

[5] Toth, Z., I. Szunyogh, C. Bishop, S. Majumdar, R. Morss,, and S. Lord, 2001: On the use of targeted observations in operational numerical weather prediction. Preprints for the Fifth Symposium on Integrated Observing Systems, January, 15–19, 2001, Albuquerque, NM, AMS, 72–79.

[6] Leutbecher, M., and A. Doerenbecher, 2003: Towards consistent approaches of observation targeting and data assimilation using adjoint techniques. Geophysical Research Abstracts, Vol. 5, 06185, European Geophysical Society.